

Concept of Powerful Multistage Coaxial Cyclotrons for Pulsed and Continuous Beam Production.

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Abstract

The concept of large-radius multistage coaxial cyclotrons having separated orbits is described, to generate proton beams of 120-2000 MeV energy at tens of GW pulsed and hundreds of MW in continuous beam power operation. Accelerated beam losses must be less than 0.1 W/m for the intercepted average beam power linear density.

The concept is inherently configured to actively compensate the longitudinal and transverse space charge expansion in beam bunches. These are based on (1) actively varying the bunch acceleration equilibrium phase while maintaining isochronism, independently for each cyclotron turn; (2) independently changing the acceleration voltage for each turn together with orbit corrections that preserve isochronism; (3) independently changing the transverse betatron oscillation tune shift, to assure non-resonant operation. Also, (4) sextupole lenses are included to compensate for chromaticity effects. Moreover, the concept is based on optimum uses of practical successful results so far achieved in beam acceleration and storage techniques.

These are the reasons why the proposed multistage cyclotron system appears doable. This accelerator has a wide range of applications. It can especially be used to deliver a pulsed intense source of neutrons for scientific research without the use of follow-on storage rings for pulse compression, and also, to drive the industrial transmutation technologies.

As an example of such a cyclotron system, we describe our approach of accelerating single-bunch proton beams at up to 1 GeV energy, with pulsed beam power of 80 GW and bunch duration of 2 ns. The exemplar cyclotron accelerator system is configured to be located in the shielded structure of the 6-GeV Yerevan Electron Synchrotron. The cost of such a cyclotron system is estimated to be approximately 40,000,000 US dollars, if implemented in Armenia at substantially reduced labor costs.

1 Introduction

High power proton or ion accelerators at hundreds MW in continuous mode are needed for the Accelerator Driven Transmutation Technologies (**ADDT**), in different nuclear power production industrial applications. However, the same cyclotron accelerator system can also be applied to produce ultra-short beam pulses for scientific investigations, for the production of powerful neutron sources. In this case, generated pulsed beams may have peak power in the range of 10-100 GW. If in addition the duration of ejected pulsed beams is less than 1.0 ms at energies of 1.0 GeV, it is also possible to exclude the necessity of placing a last-stage storage ring for pulse compression to produce intense neutron bursts [1,2].

This work is performed to optimize plans for the construction of a proton accelerator system with 1.0 GeV energy and tens of mA current, to be realized in the existing shielded structure of the

Yerevan 6-GeV Electron Synchrotron. The primary approaches, based on the use of large-radius isochronous Coaxial Ring Cyclotrons (CRC) and Asynchronous Cyclotrons (AC) were described in references [3-7].

The key problems that relate to the construction of powerful proton accelerators are the following: - To greatly decrease the beam losses - To increase the efficiency and reliability of accelerator's with reduced operating costs - To decrease the development and construction costs.

The most difficult problem is to get high values of average beam current with acceptably low values of accelerated beam losses.

2 Concept of multistage coaxial cyclotrons

The concept of Multistage Coaxial Cyclotron (**MCC**) gives an opportunity to perform flexible management of separated cyclotron orbits in the energy range of 120-2000 MeV, and to also obtain hundreds of mA average beam current in continuous beam operation. These advantages are based on demonstrated accelerator physics and technologies that have been implemented predominantly on powerful synchrotrons and linear accelerators (linacs).

We first note that on HERA [8,9] it has been demonstrated that injection and acceleration of proton beams in synchrotrons (without storage) proceed well when the number of particles in each bunch is limited to $(1.2 \div 1.4) \times 10^{11}$, for acceleration frequencies of 10-100 MHz and energies of tens of MeV to tens of GeV.

Second, in the same publications it is shown that due to high-precision strong focusing and high vacuum, beam losses during many years of HERA machine operation have not exceeded the tolerable value of 0.01 nA/m, for energies higher than 100 MeV.

Third, in modern high power linacs [10,11], the construction, transmission and handling of megawatt level RF power from single sources have been demonstrated at frequencies of 350-700 MHz. In principle, it is also possible to develop similar approaches for large acceleration cavities [12,18] and low frequencies of 50-100 MHz.

It also appears that in a large radius **MCC** it would not only be possible to create conditions like those existing in proton synchrotrons for strong longitudinal and transverse beam focusing, but to attain much better conditions due to the possibility of the more flexible and relative independent management of the separate orbit parameters.

Thus, if we set the acceleration field of cyclotrons to have a frequency in range of 50-100 MHz and as obtained at HERA, limit the number of particles per bunch to $(1.2 \div 1.4) \times 10^{11}$, in continuous mode of operation an average acceleration current of up to one Ampere $[(1.2 \div 1.4) \times 10^{11} \times (50 \div 100) \times 10^6]$ should be feasible for reasonably low beam interception losses.

In order to realize such a **MCC**, the structure, the number of stages and their parameters will be chosen according to the following considerations:

1. In order to provide for flexible longitudinal beam focusing, the opportunity of independently tuning in a wide range of up to tens of degrees of equilibrium phase in acceleration fields will be exercised, in one or two pairs of turn sectors, in each separate orbit turn while maintaining isochronism.

2. To create a strong and quality transversal focusing of beam, the providing of enough space between the accelerating cavities to install the warm magnet system with separated functions and with additional sextupole lens to correct the chromaticity and also to change the mechanical coordinates of magnet elements in the range of several millimeters and length of bending magnets in the range of several centimeters.

3. In order to increase the efficiency and simplify the injection and ejection of beams, the parameters of **MCC** stages is tuned to be possible to put these stages coaxial or concentric, each into the other.

4. In order to increase the opportunities of beam parameter's tuning, the value of the turn separation is chosen to be more than 20cm. and camera's aperture, not less than $3 \times 5cm$.

5. To compensate the shift of bethatron oscillations frequency from the effect of the beam space charge, the opportunities of slow changing of Q value from one magnet period to the other in according with computer code and depending of measured beam parameters, are supposed.

6. The cavities could be warm as well as superconducting (**SC**). The choice depends on a lot of reasons and the firstly on opportunities and tastes of desingners.

7. In order to increase the opportunities to compensate the mutual influence of beams into the accelerating cavities and spread of cavities' parameters during the accelerator tuning, besides of conditions 1, the opportunities of independent changing of accelerating voltage on each beam's channel, using not mechanical methods is supposed.

8. It's reasonable to create the **MCC** on energies more than 120MeV. Lower energy accelerators seem to be not satisfied from technical point of view, because of essential decreasing the "RF acceptance" value and increasing of the tolerances on the magnetic field's quality. That becomes more remarkable at high values of harmonic h of accelerating RF field, however, on the other hand the stable operation of accelerator usually is easily realized on super narrow phase width of accelerating beam. The upper value of energy does not limited, because of formal technical reasons are absent and only economical reasons could be mainly considered, acceptable limit for which seems to be around 2000MeV.

9. Nowadays opportunities to construct the proton accelerators with energy up to 120MeV are wide enough, starting the RFQ and finishing the **SC** Cyclotrons with Separated Orbits. That's why the decision of question concerning the Project of injecting system with final energy up to 120MeV depends on opportunities and tastes of designers and will be considered separately.

10. The price of construction and exploring of **MCC** should be essential lower the price of adequate Linac.

11. Developing of **MCC** Project must be also based on enough studying of experience and results of designing and construction of similar cyclotrons with separated orbits [13, 17].

3 **MCC** pulsed operation mode

Anyway, even constructing the **MCC** with continuous functioning, it's reasonable to have opportunity to realize initial adjustment and start up of accelerator in pulsed mode and rather with acceleration of one-bunch beam, which is formatted into the injector's structure. The radius of the last stage of **MCC** is chosen from the condition to provide the duration of one turn of beam to be less than 1.0 mksec., in order to satisfy the requirements applied to using proton beam into the system of neutron source. Thus, if the peak value of current for accelerating beam in **MCC** will be high enough (about tens Ampere), then it's not necessary to create the storage rings [1, 2].

During one-bunch regime of **MCC** operation, in any time only one bunch will pass any cavity, and time interval between loading the cavity by beam (bunch) is equal the duration of one turn of beam at given stage. Instabilities at such regime of operation and essential limitation of intensity (took place in regime of continuous acceleration of beam), connected with these instabilities , are just disappeared.

So, during the short pulsed feeding of cavity (20-40mksec.), depends on the level of connection with the RF generator and quality factor , it's possible to increase significantly the value of electrical field in cavity(before appearance of multiplicity effects) and use the warm cavities.

However, in the same time it seems to be not technically profitable the construction of pulsed feeding for Magnet Elements (**ME**- bending magnets and lenses) during the period of the pulsed mode accelerating in **MCC**. The explanation is, that for pulsed feeding of **ME** the distortions and instabilities of the **ME**'s magnetic fields are dramatically increased. This is connected mainly with drifting of "coercivity" of the magnet's core iron, and demagnetization by inverse polarity current is not enough stabilizing effect, particularly for the edge of magnet and short lens.

Besides that, the pulsed feeding determines the necessity of **ME** construction, using more thinner of sheet steel, that leads to the increasing of mechanical distortions of the core. Moreover, the isolation of winding increases, that leads to the according increasing of the **ME** sizes. As a result, the opportunities to construct small sizes **ME**, which are very important for considered type of cyclotron, are decreased. So, the **ME** feeding system becomes complicated, particularly the possibilities of precise stabilization of this system. The main thing is, that identity of such magnet system will be destroy during the transition from pulsed to continuous feeding.

That's why the chose of continuous current for the **ME** feeding, during the pulsed one-bunch beam acceleration in **MCC**, will allow to move smoothly to multi-bunches acceleration up to continuous regime. That is possible only at the expense of the RF system power increasing and seems to be technically justified.

Anyway, initial tuning of the **MCC** with one-bunch acceleration in each cycle of accelerating open also some additional opportunities to increase the quality of cyclotron. For example, it's possible to identify by help of the same bunch all detectors and also some others parameters of cyclotron in all channels and stages. Besides that, cycling rate can be not only 50-60Hz, but will be varied in a wide range from zero up to several thousands Hz.

Described advantages of one-bunch acceleration, will allow, in roughly estimation, to increase the number of particles in single bunch more than in one order, e.g. to reach the values of 10^{12} and more. Taking in account, that phase duration of bunch is usual about 0.1 of oscillations period of accelerating RF field in cavity, then, at the RF oscillations frequency about 50MHz, the pulsed power of ejected **MCC** beam at energy about 1GeV will be about 80 GW with pulse duration equal to 2ns. It seems to be enough to construct the powerful pulsed neutron source without the storage ring [1, 2].

For the future, with each increasing of bunches number, the number of stable accelerating particles in each bunch will be a little decreased. This process will be continued till the reaching of the continuous mode, after that process will mainly finish. However, if **MCC** system is constructed and adjusted correctly, then the number of particles located in each bunch at continuous regime should not be less the value already reached on practice, e.g. 10^{11} .

With increasing of average current of beam it's necessary to have mainly according increasing of accelerating RF system power, what is mainly connected with financial opportunities. Thus, one more practical advantage of suggested type of accelerator is the possibility of the gradual upgrade of it power without changing of structure and magnet system, any upgrade depends just on financial opportunities.

It will be not so correct to estimate generally the cost of **MCC**, because of strong dependence on the "making" country. Because of that, we will initially consider some relative cost reasons in comparison with Linac, which seemed to be independent enough from the "making" country.

For example, the length of Linac at 1GeV energy in SNS and **ADDT** systems [1, 2, 10, 11] is about 1.0 km. Then the length of shielding concrete wall of 3m thickness will be about 2km. While, the same external wall for **MCC** with similar parameters of beam and with final radius about 38m(see bellow), will have a length almost in one order shortly. One can expect, that also the cost of expensive wall will decrease about ten times. Besides that, the cost of accelerating RF technique on 50MHz frequency is usually significantly lower than for similar technique on 350 and

700MHz frequencies. Approximate picture of cost values for suggested type accelerator construction one can image, based on the estimations of four-stage **MCC** construction at 1GeV energy for one-bunch accelerating of beam at Yerevan Physics Institute (YerPhI) in to existing radiation zones of electron synchrotron at 6GeV(see below). Based on results of these estimations we can conclude, that construction of **MCC** will take about 40,000,000 US dollars, what is more than one order less than cost of construction of similar accelerators, described in [1, 2, 10, 11]. We should note, that obtained estimation of cost does not include the cost of shielded structures, manpower and cost of 120MeV injection system construction. The cost for injection system is estimated in about 15% of total sum. The manpower and shielded structures cost essentially depends on current economical status in the "making" country.

4 MCC based on YerPhI synchrotron

The aim of this work is to try to demonstrate the principal possibility and advantages of a wide-applicable **MCC** based on example, developed for YerPhi , relative to similar accelerators.

The following data are used as a basis of calculations: the main ring average radius is 34.5 m, the tunnel width is 6.0 m, with 3.0 m thick tunnel walls, and the inner circular hall diameter is 57.0 m. As shown in Fig. 1, the first three cyclotron stages are nested and concentrically installed in the hall, acting as injectors for the fourth stage cyclotron in the **YerPhI** main-ring tunnel.

The choice of **MCC** structure and its parameters depends on the choice of the type and parameters of the accelerating RF cavities. In [15, 16, 17] the research and design of large, low-frequency (90-170MHz) accelerating **SC** cavities with no spherical symmetry and with substantial radial range of gap are described. In these cavities, as well as in large warm ones, which have the radial range of working gap more than 4m and 50MHz frequency [12, 8], the inner active surfaces are made of Pb or PbSn(4Sn 96Pb atoms). At the same time, in warm cavities, the electrical fields of 6.2Mv/m are reached, and in **SC** - 10.6Mv/m, while the ratio of the total electric field to the using part of field is $E_{peak}/E_{acc} = 1.5$. For the proposed four-stage **MCC-YerPhI** the warm cavities' design is taken into account, similar to those modeled in [18] based on the presently operating in PSI [12] modern cavities, at 40-50MHz frequencies and achieving peak voltage of up to 1.1MV, with radial range of working gap up to 4m. The results of calculations for one of the versions of **MCC-YerPhI**, consisting of 4 rings are given in Table 1.

The transit-time factor value is assumed to 0.95. The magnet period structure is assumed as FODO lattice with separate function.

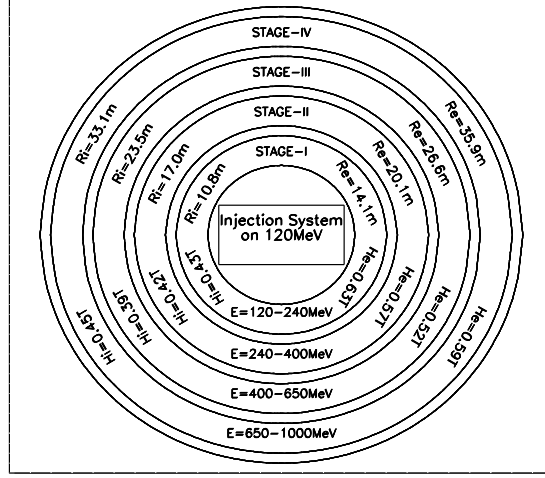


Figure 1: *General layout of the Yerevan 1GeV MCC proton accelerator.*

Table 1: *Four stages MCC-YerPhI parameters*

PARAMETERS	STAGE-1	STAGE-2	STAGE-3	STAGE-4
E_i -Injected Beam Energy [MeV]	120	240	400	650
E_e -Extracted Beam Energy [MeV]	240	400	650	1,000
R_i -Injection Beam Radius [m]	10.8	17.0	23.5	33.1
R_e -Extraction Beam Radius [m]	14.1	20.1	26.6	35.9
N_c -Number of Acceleration Cavities	10	15	22	40
N_m -Number of Sector Magnets	110	150	230	320
N_q -Number of Quadrupole Lenses	220	300	460	640
N_s -Number of Sextupole Lenses	220	300	460	320
H-Field in Sector Magnets [T]	0.43-0.63	0.42-0.57	0.39-0.52	0.45-0.59
G-Gradient in Quadrupoles[T/m]	1.65-1.82	2.47-2.78	2.98-3.56	4.20-5.30
ΔE -Energy Gain per Turn [MeV]	11.0	16.5	24.2	44.0
ΔR -Orbit Separation [cm]	39.9-23.5	40.0-24.9	39.7-22.4	46.9-26.1
Q-values	3.75	5.75	7.25	10.25
n-Number of Turns	11	10	10.5	8
h-Harmonic Number	25	30	35	43
L_m -Length of Sector Magnet [m]	2.3	2.3	2.3	1.5
L_f -Length of Drift Spase [m]	4.1-6.1	4.3-5.6	3.9-4.8	3.2-3.7
Total Weight of Sector Magnets [tonne]	178	243	372	328

Table 1 shows, that the orbit separation is in the range of 40-23cm., and the length of drift

space is not less than 3.7m, which will allow not only to place freely focusing magnet elements and detectors , but also to easily provide 100% beam ejection. The total value of turns in the **MCC-YerPhI** will be 39.5 .

Table 2 shows the computer calculations for the first turn of beam in the first stage of **MCC**, at artificial change of equilibrium phase on +3.6 degree in sector 5 and on -3.6 degree in sector 6, while maintaining isochronism.

Table 2: *Change of Bunch Equilibrium Phase versus Sector Magnetic Field Setting in the First Turn of a Separate Orbit Cyclotron(SOC).*

Sector# Around 1 st turn	q= h/N_c	dE MeV/ Cavity	r[m] Bending radius	R[m] Orbit radius	L_a [m] Left Drift length	L_b [m] Right Drift length	L_m [m] Sector Magnet length	[Tesla] Field in Sector magnets	E [MeV] Beam energy
1	2.5	1.1	3.73	10.852	2.367	2.247	2.344	0.439	121.09
2	2.5	1.1	3.73	10.894	2.385	2.256	2.344	0.441	122.19
3	2.5	1.1	3.73	10.932	2.392	2.274	2.344	0.443	123.29
4	2.5	1.1	3.73	10.973	2.410	2.283	2.344	0.445	124.39
5	2.51	1.1	2.41	11.011	2.844	2.729	1.516	0.693	125.49
6	2.49	1.1	5.12	11.057	1.992	1.850	3.217	0.327	126.59
7	2.5	1.1	3.71	11.083	2.429	2.347	2.337	0.453	127.69
8	2.5	1.1	3.73	11.135	2.477	2.317	2.344	0.454	128.79
9	2.5	1.1	3.73	11.160	2.448	2.371	2.344	0.456	129.89
10	2.5	1.1	3.73	11.211	2.501	2.343	2.344	0.458	131.00

According to the evaluated errors in the dipole and quadrupole alignment, the beam envelope, including orbit distortions, was computed. It sizes in different stages of **MCC** lies within the limits of $40mm \times 60mm$ and determines the aperture and outside dimension of magnets, the latter of which are $20cm \times 20cm$. For the calculations the followings values of injecting beam emittance were taken: $E_x = 15\pi \times mm \times mrad$ and $E_z = 10\pi \times mm \times mrad$.

Table 3 shows the main parameters of extracted beam and cost estimations of **MCC-YerPhI** construction in two cases of accelerator functioning. The continuous regime of hundreds MW beam production is not considered, because of low probability to realize it at YerPhI, due to the financial reasons. Still, one can easily obtain from these tables the main information to approximate more powerful continuous regime of accelerators' functioning.

Table 3: *Bunch Parameters of Separate Orbit Cyclotron in Single Bunch and Multiple Bunch Operations and Related Cost Estimates*

PARAMETERS	SINGLE BUNCH MODE	MULTIPLE BUNCH MODE
Beam Specie	Proton	Proton
Beam Output Kinetic Energy	1.0GeV	1.0GeV
Number of Bunches per acceleration Cycle	1	25
Bunch Duration	2ns	2ns
Beam Pulse Length	2ns	500ns
Number of Protons per Bunch	10^{12}	10^{12}
Cycle Repetition Rate	50Hz	50Hz
Average Beam Power	8kW	200kW
Instantaneous Beam Current	80A	8A
Instantaneous Beam Power	80GW	8GW
Average Beam Loss Power	0.1W/m	0.1W/m
Total Electric Power	2.6MWe	2.7MWe
COST ESTIMATION	Million US\$	Million US\$
87 Acceleration Cavities, each at \$150k	13.05	13.05
RF Generators, at \$2.5M per MW(rf)	For 0.096 MW(rf)=0.24	For 0.29 MW(rf)=0.73
820 Bending Magnets, each at \$10k	8.20	8.20
2,920 Lenses, each at \$3k	8.76	8.76
Vacuum System	3.50	3.50
Accelerator Control System	2.50	2.50
Other Miscellaneous Items	1.50	1.50
COST TOTAL	37.57	38.74

One can see for this type of machine, that it's profitable to choose the low values of RF accelerating frequency, because that makes accordingly easy the problem of precisions, almost for all systems, but on the other hand, the problems to get the high values of electric fields into the cavities and their quality factor(Q) become complicated, although in **SC** case this effect is weaker displayed.

Besides that, high values of the harmonic number lead to the increasing of opportunities to tune of equilibrium phase and stability of acceleration. Therefore, the necessity to search the compromise decisions is obvious. To increase the quality and stability of **MCC** acceleration, the installation of sextupole lenses near the quadrupole lenses in the area of non zero dispersion orbit to compensate the chromaticity is foreseen. It's also foreseen to construct the electronic systems of inverse connection with controlled passing strip and with feed of correcting voltage on special electrodes as well as application of others known methods. All these methods, including a new developed ones, will provide the minimal beam losses during the accelerating over the spiral orbit with varying orbit separation value.

5 Conclusions

The main goal of given work is to demonstrate, that it's very important to continue design, developing and improvement of such a new, perspective type of accelerator as **MCC** complex, which

will be useful not only for scientific investigations, but also for nuclear industry. In conclusion, the authors would like to thank the colleagues from YerPhI, particularly A.Ts. Amatuni and colleagues from JINR (Dubna) for useful discussions and remarks.

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